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Mapping the Dust Distribution in Circumstellar Debris Disks by Combining Multiwavelength Images

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ABSTRACT

We have developed an inversion procedure (DISKFIT) that is designed to estimate the two-dimensional spatial distribution of dust optical depth (or relative column density) in the plane of a circumstellar debris disk, given a set of observed images at multiple wavelengths, with or without SEDs, and with certain model assumptions. The column density distribution for Fomalhaut has been derived using the Spitzer data at 24, 70, and 160 μm.

Subject headings: techniques: image processing — stars: imaging — stars: planetary systems

1. Motivation

This tool was developed to aid in the interpretation of multiwavelength images and SEDs of circumstellar disks in a way that separates the effects of spatial variations in column density from those of dust temperature. This facilitates a comparison with the results of dynamical modeling.

2. Physical Assumptions in Current Implementation

1. The wavelength variation of opacity is the same throughout the disk.

2. The radial variation of dust temperature is given by the energy balance of individual grains (Backman & Paresce 1993), and is based on an assumed characteristic size scale of the grains (equal to 27 μm for Fomalhaut, based on an analysis of the SED by those authors).

3. The vertical scale height of the disk is proportional to radial distance.

3. Algorithm

Step 1. Parameter Estimation

In this initial step, a simplified model is used in order to obtain approximate values of some basic parameters. For this purpose, we assume a circular disk with a power-law radial dependence of optical depth. A maximum likelihood estimate is made of the full set of parameters characterizing this model, using the set of observed images and corresponding point spread functions (PSFs). The complete set of parameters involved, together with their estimated values for Fomalhaut (using data at 24, 70, and 160 μm) is as follows:

$i = 68^\circ \pm 3^\circ$ (Inclination with respect to the plane of the sky)

PA $= 24^\circ \pm 1^\circ$ (Position angle of tilt axis)

$r_{\rm in} = 111 \pm 10$ AU (Inner radius)

$r_{\rm out} = 373 \pm 45$ AU (Outer radius)

Opening angle $= 9\overset{\circ}{.}0 \pm 0\overset{\circ}{.}1$ (Opening angle for the flared-disk geometry)

$\tau(r_{\rm in}) = (1.10 \pm 0.03) \times 10^{-3}$ (Optical depth at inner radius at a reference wavelength of 24 μm)

$\alpha = -1.74 \pm 0.05$ (Power-law index for radial variation of column density)

$\beta = -1.00 \pm 0.01$ (Power-law index for wavelength variation of opacity)

Note: The quoted error bars are the formal errors of the maximum likelihood fit, and represent the effect of random measurement noise, excluding the errors of absolute calibration. Since the measurement model is nonlinear, these error bars represent *lower bounds* to the actual uncertainty values.

Step 2. Inversion for Optical Depth Map

Based on the inclination, position angle, opening angle, and wavelength opacity index estimated in the previous step, the full inversion for the 2-d distribution of line-of-sight optical depth (referred to as a "taumap") in the plane of the sky is accomplished using an algorithm, mathematically similar to Richardson-Lucy (Richardson 1972, Lucy 1974). Since the PSFs at each wavelength are implicitly deconvolved using the prior knowledge of positivity of optical depth, some super-resolution is obtained.

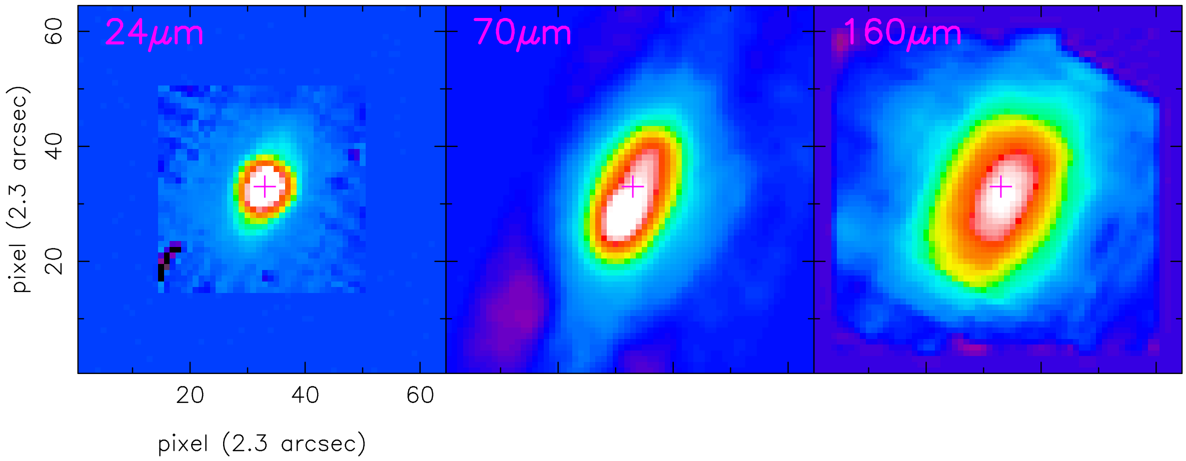

Fig. 1 Input images. Spitzer images of Fomalhaut at 24, 70, and 160 μm. The field of view is approximately 150 arcsec in each case. The estimated photospheric contribution of the central star has been subtracted from the 24 μm image.

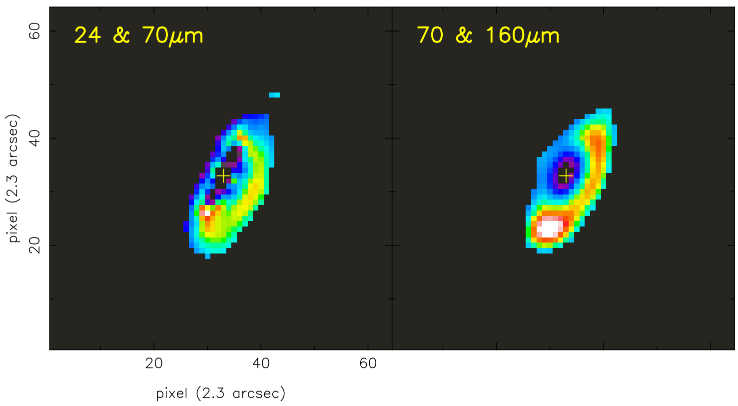

Fig. 2 Projected Column Density in the sky plane. Estimated distribution of line-of-sight optical depth, projected in the plane of the sky as obtained *(left)* using 24 and 70 μm . *(right)* using 70 and 160 μm. The field of view is 1120 AU.

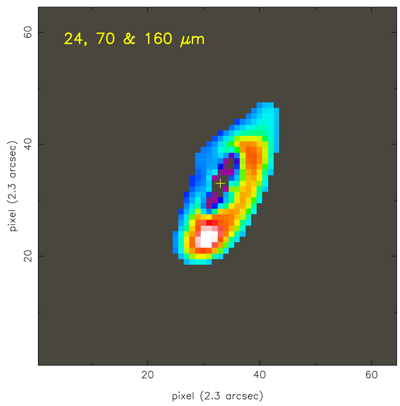

Fig. 3 The line-of-sight optical depth, projected in the plane of the sky, obtained using all three wavelengths (24, 70, and 160 μm).

4. Column Density Distribution in the Disk Plane

In the limit of a geometrically-thin disk, the sky-plane projection can be converted to a disk-plane (pole-on) view using a simple coordinate transformation. For a disk of finite thickness (nonzero opening angle), the pole-on taumap requires a nonlinear estimation procedure, and is currently under development.

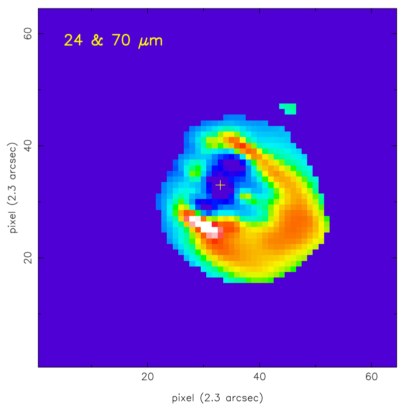

Fig. 4 Column Density Distribution in the Disk plane as derived from the 24 and 70 μm data. Since the estimated opening angle of the disk (from the initial parameterized fit) was zero, we can, in a self-consistent way, convert the sky projection into a disk-plane view using a simple coordinate transformation. This approximation becomes invalid when the longer-wavelength data (160 μm) are included, since effects of the finite opening angle become

much more significant. (The estimated values of opening angle were 9° and 20° for the cases 24+70+160 μm, and 70+160 μm, respectively).

5. DISKFIT as an Interface Tool Between Observed Images and Dynamical Disk Models

- The output is a "taumap" at a specified reference wavelength, corresponding to relative column density, free from the effects of the spatial variation of dust temperature.
- Can combine both images and SEDs to constrain the inversion consistent with the data and their PSFs.
- Achieves spatial resolution enhanced reconstruction and inversion to a degree determined by the weighted PSFs of individual images and SEDs.
- The taumaps provide a natural interface between the observations and the predictions of dynamical modeling.
- Although we have shown here its application to a well resolved disk, we expect that it will be a useful tool for the analysis of the large number of expected marginally-resolved disks. In those cases, it will be appropriate to take the analysis only as far as the parameterized fit.
- Our present results for Fomalhaut suggest that some of the asymmetry in the strengths of the two main features apparent in the intensity maps is a result of differences in column density rather than dust temperature.

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